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This keynote presentation Tu-KEY-01 was given at ISEC 2017.

ISEC 2017
Sorrento, Italy
June 13, 2017

Tu-KEY-01

Impact of Recent Advancement in Cryogenic Circuit Technology

Akira Fujimaki and Masamitsu Tanaka
Nagoya University

Acknowledgment
This work was supported by JST ALCA and JSPS KAKENHI (Grant Numbers 16H02340, 26220904, and 16H02796), JST-ALCA and the VLSI Design and Education Center of the University of Tokyo, in collaboration with Cadence Design Systems, Inc. The circuits were fabricated in CRAVITY of AIST.

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What we have introduced to superconductor circuits within the past decade?

T

Locally generated heat is introduced, opening
'**Superconductor phononics**',
'**Superconductor phonon engineering**' ?

H or θ

Ferromagnetic materials are introduced,
opening '**Superconductor spintronics**',
or '**Superconducting phase engineering**'.

I Only currents are used for controlling circuits.

Increased degree of freedom

Logo of ASC

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Outline

- Introduction
- More SFQ
  - More powerful computing
  - More energy-efficient computing
- Superconducting Phase Engineering
- Superconductor Phonon Engineering
- Summary

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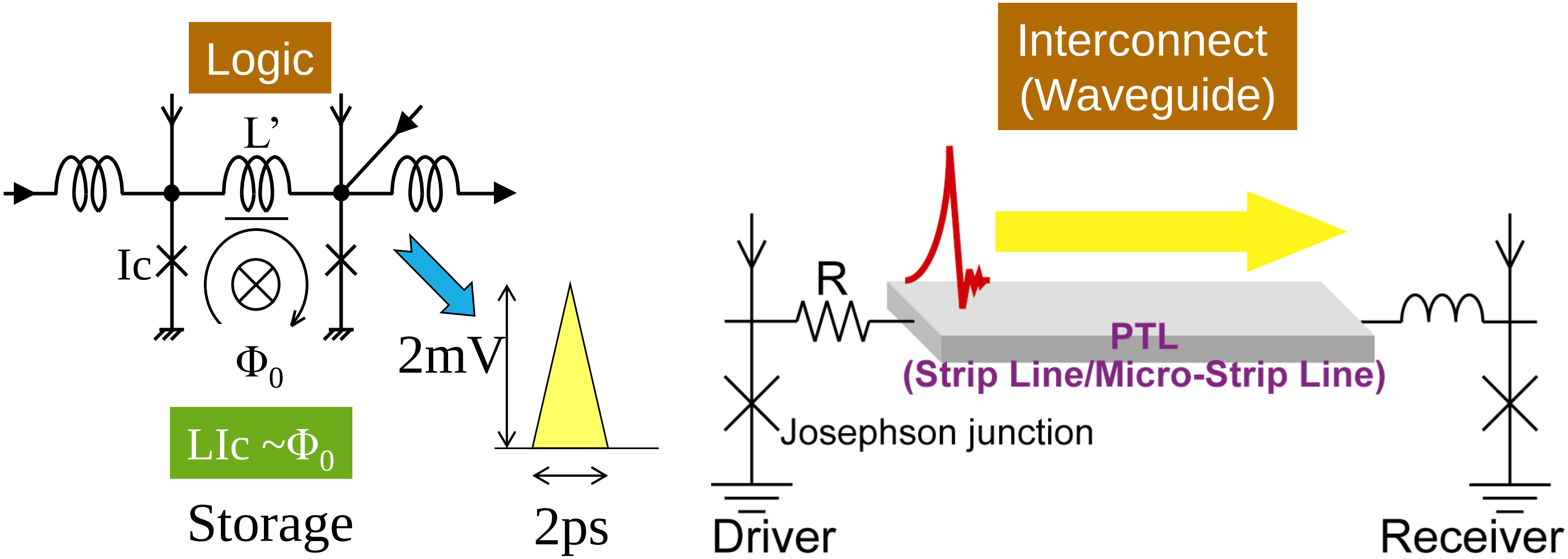
Special Features of SFQ Circuits

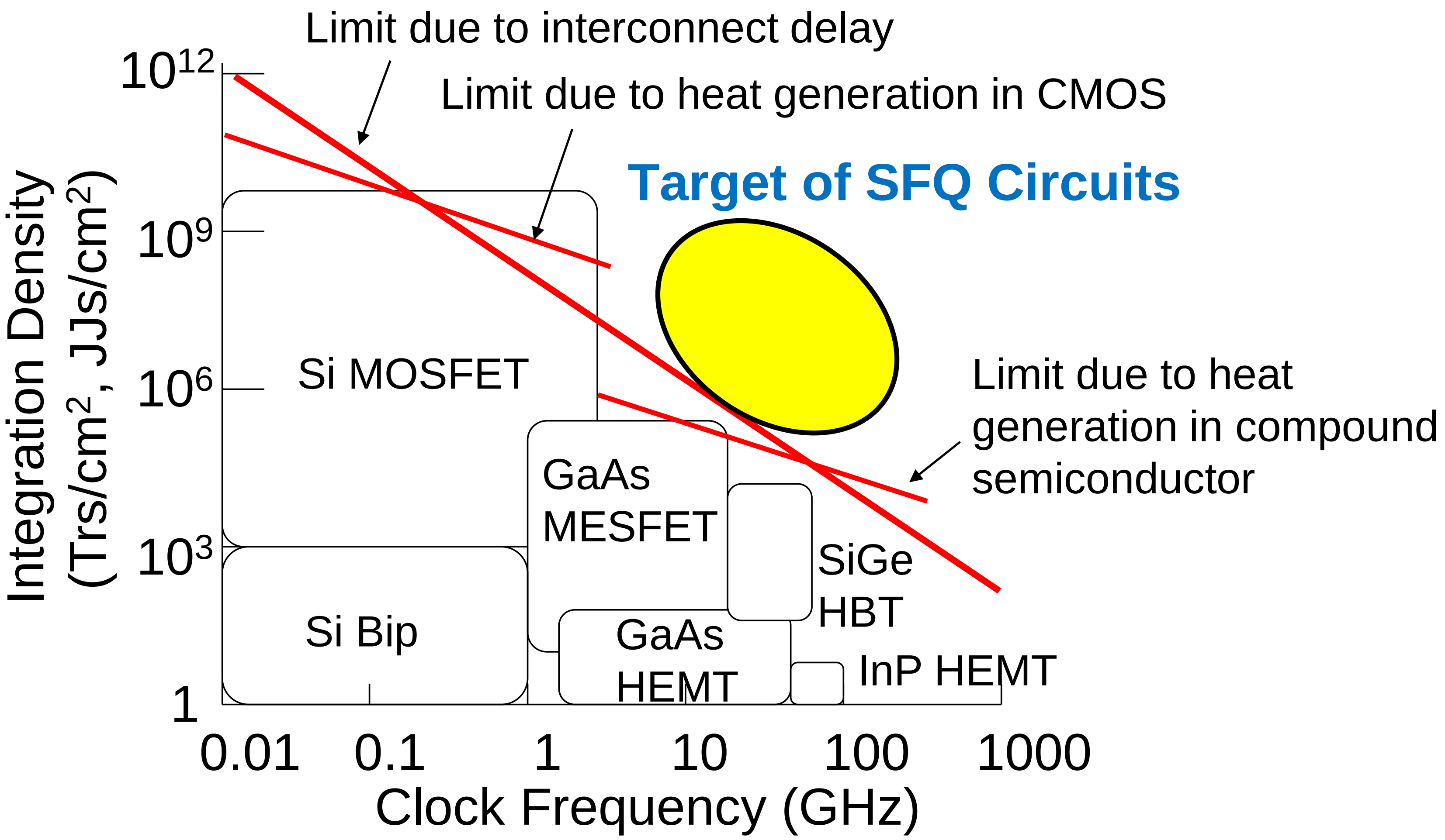


- Signal propagation at the speed of light with small distortion in interconnects based on waveguides.
- No recharge process both in logic operation and interconnects.
- Scaling law

→ High-speed & low power

→ Suitable to LSIs

Appealing Feature of SFQ Circuits



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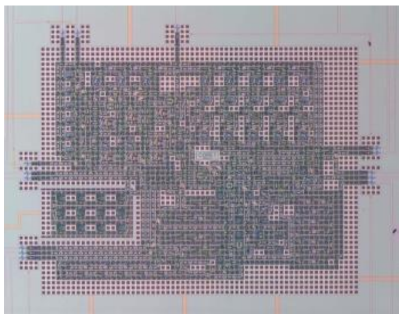
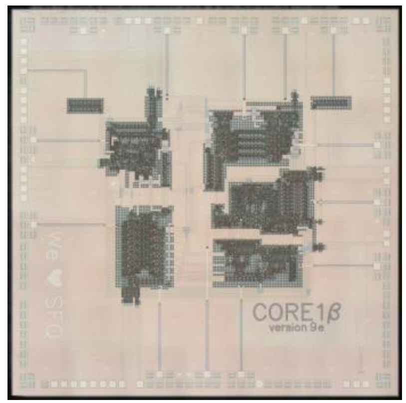
History of RSFQ Microprocessors



CORE1α (2003)
4999 JJs
15 GHz
167 M Instructions/s
1.6 mW



CORE1β (2006)
10955 JJs
25 GHz
1400 Million Operations/s
3.3 mW

What's next?

- More Powerful
- More Energy-Efficient
- More Flexible

The base of the new computational paradigms
- ✓ Adiabatic
- ✓ Reversible
- ✓ Neuromorphic
- ✓ …

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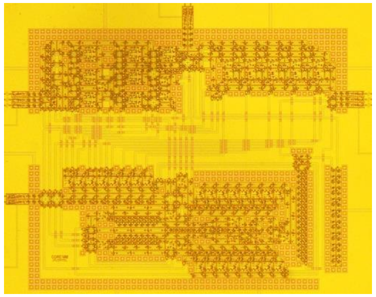
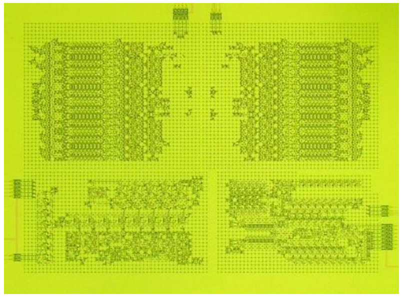
More Powerful Computing Based on RSFQ

Bit-serial μP
100 GHz
μP w/o Memory



CORE100 (2015)
3073 JJs
800 MIPS
1.0 mW
800 GIPS/W
New Fabrication

Bit-serial μP
50 GHz
Memory Embedded



COREe2 (2017)
10655 JJs
500 MIPS
2.4 mW
210 GIPS/W
Programs Executed

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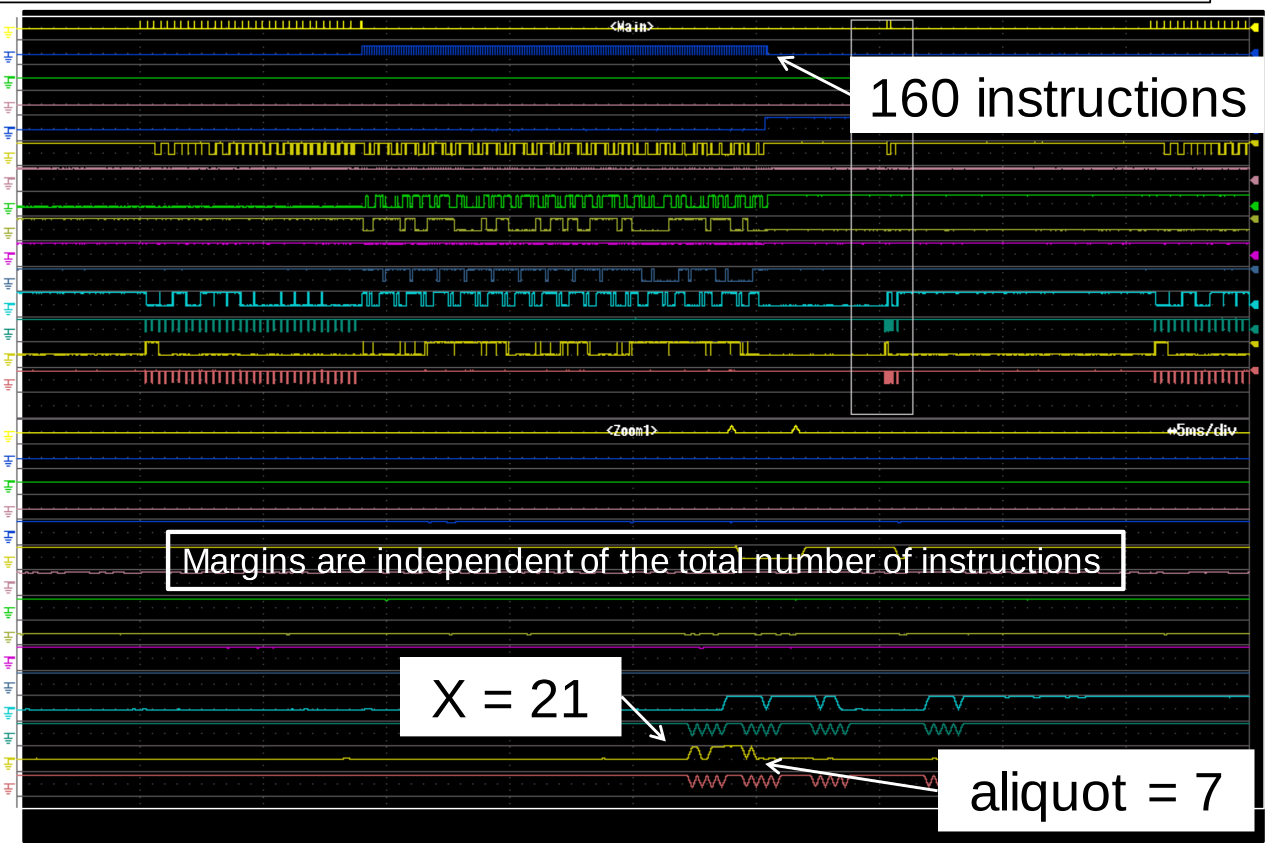
Program Execution in μ-processor COREe2

Execute a program to find a highest proper factor, which is stored in the embedded memory.

```
00:    LD  00
01:    MV
02:    DEC
03:    ST  01
04:    LD  00
05:    MV
06:    LD  01
07:    SUB
08:    SKNE
09:    HLT
0a:    SKLT
0b:    JMP 07
0c:    LD  01
0d:    JMP 01
```



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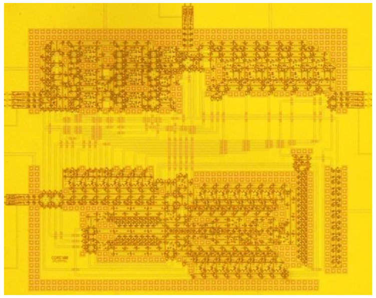
100 GHz
µP w/o Memory



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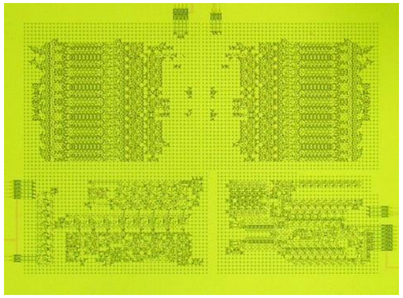
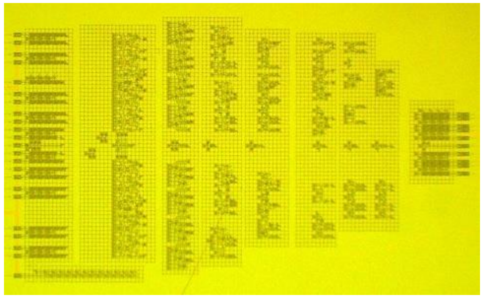
Memory Embedded



COREe2 (2017)
10655 JJs
500 MIPS
2.4 mW
210 GIPS/W
Programs Executed

Bit-Parallel ALU
50 GHz
ALU



GLP (2017)
4868 JJs
50 GIPS
1.4 mW
36000 GIPS/W
Gate-Level Pipelining

The detail will be given by Prof. Tanaka in this morning session

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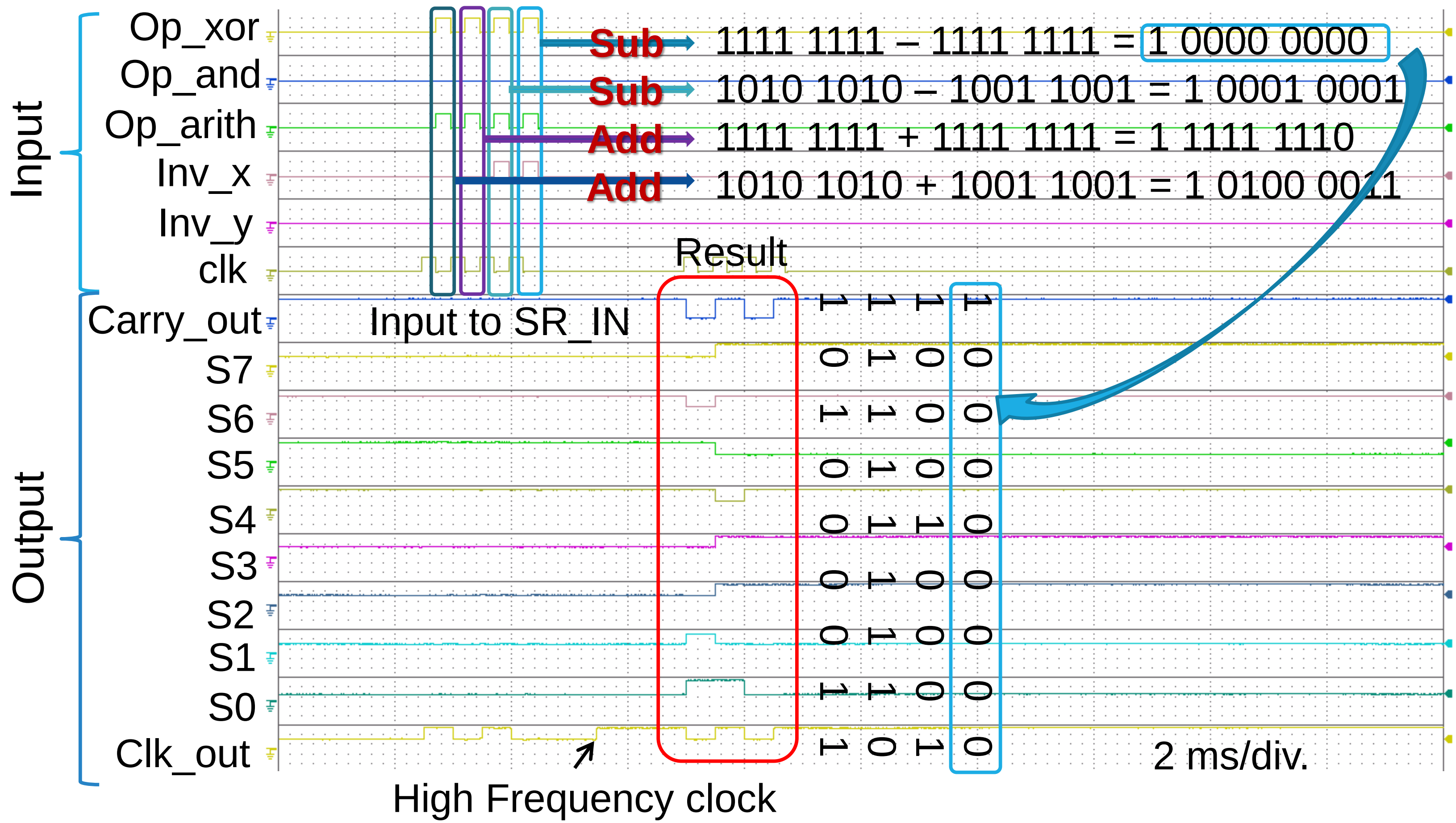
Addition/subtraction in Parallel ALU



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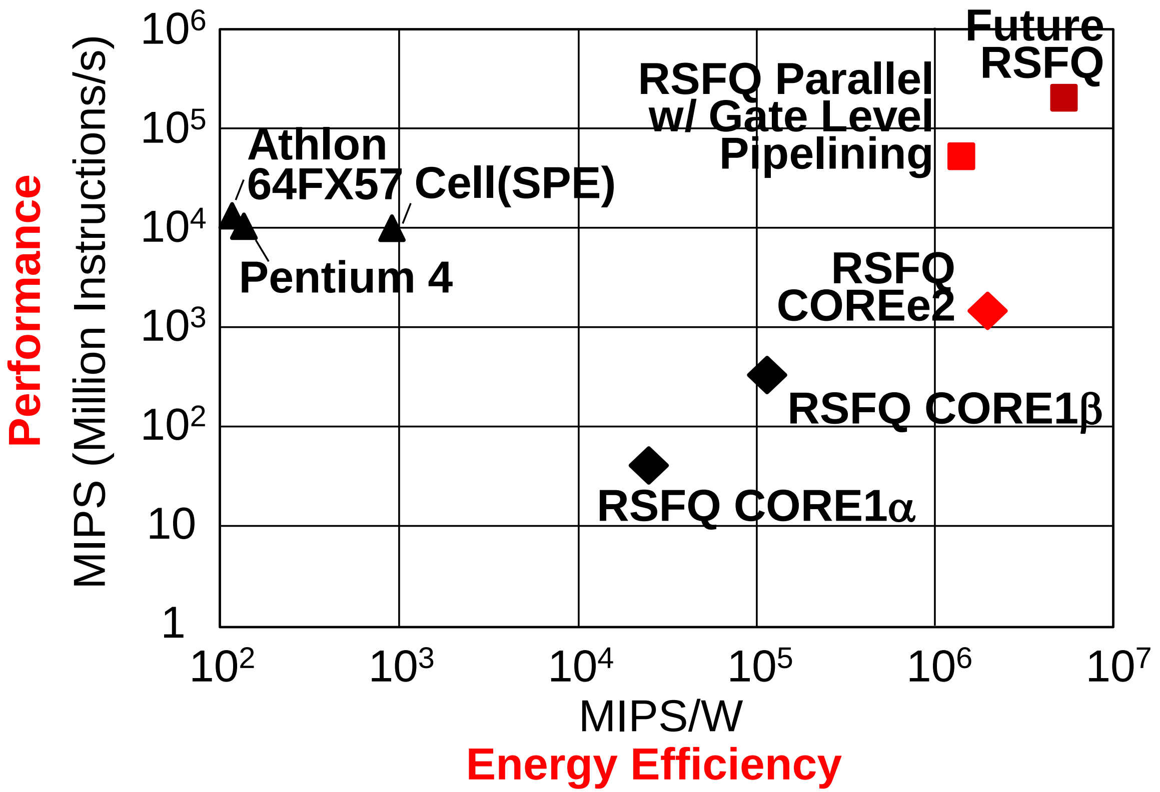
Advantage of RSFQ Technology



Estimation of performances of a 32-bit single-core microprocessor based on the experiments

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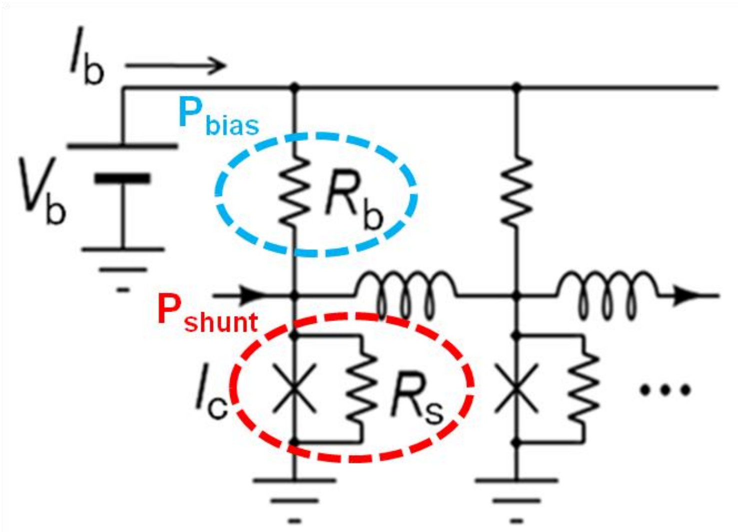
Issue for Energy-Efficiency



R_b is used for providing a constant current to each Josephson junction.

Power consumption at R_b
(Static power consumption)

$$P_{\text{bias}} = \frac{V_{\text{b}}^2}{R_{\text{b}}} \approx 0.7 I_c V_b$$

Example: DFF
$P_{\text{bias}} = 1.8\mu\text{W}$

Power consumption at R_s
(Dynamic power consumption)

$$P_{\text{shunt}} = f I_{\text{c}} \Phi_0$$

f: operating frequency

Example: DFF
$P_{\text{shunt}} = 36n\text{W}$

Typically, $I_c \Phi_0 \approx 2 \times 10^{-19} (J)$

Necessity for eliminating static power consumption.

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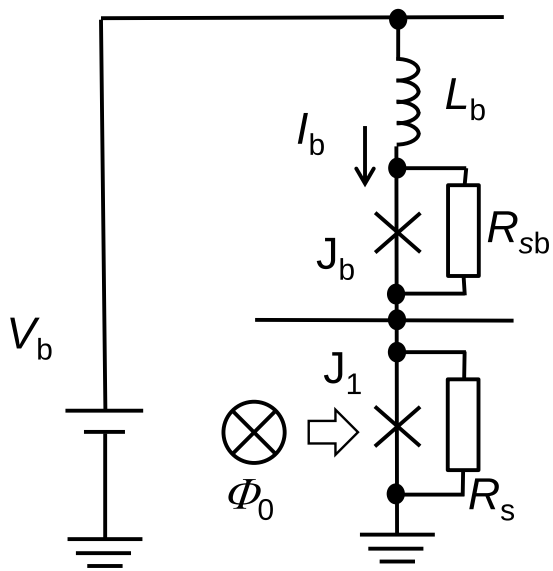
DC-Powered Energy-Efficient SFQ Circuits

Bias resistors are replaced with inductors and junctions.

ERSFQ circuit (Hypres)



D. E. Kirichenko, et al., IEEE Trans. Appl. Supercond., **21**, 776(2011).

Advantage

- The base of design has been established because resources obtained from the RSFQ circuits can be used.
- PTLs can be used as interconnects.
- Possibly suitable to higher density because no mutual coupling is used.

Disadvantage

- Difficult to make energy-efficient voltage supply around 0.1 mV.

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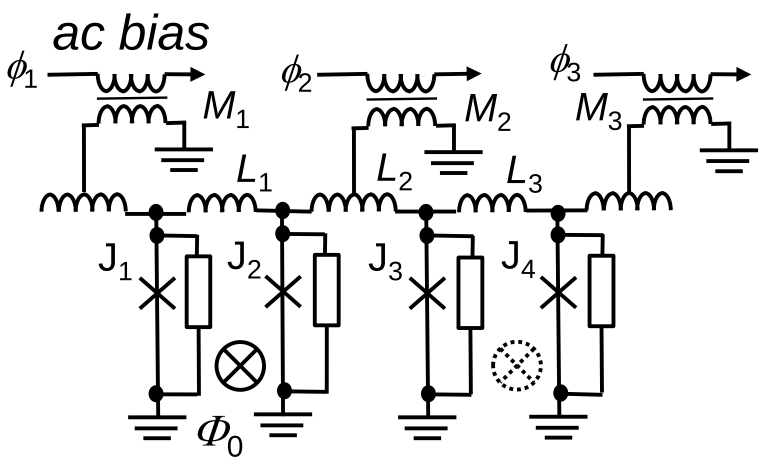
AC-Powered Energy-Efficient SFQ Circuits

Circuits are driven by AC currents provided via transformers.

Example
Reciprocal Quantum Logic
(Northrop Grumman)



Q. P. Herr, et al., J. Appl. Phys., **109**, 103903 (2011).

Advantage

- Provided AC currents are used as clock signals.
- NOT logic is easy to be made.
- The above means the RQL can be made up of smaller number of junctions.

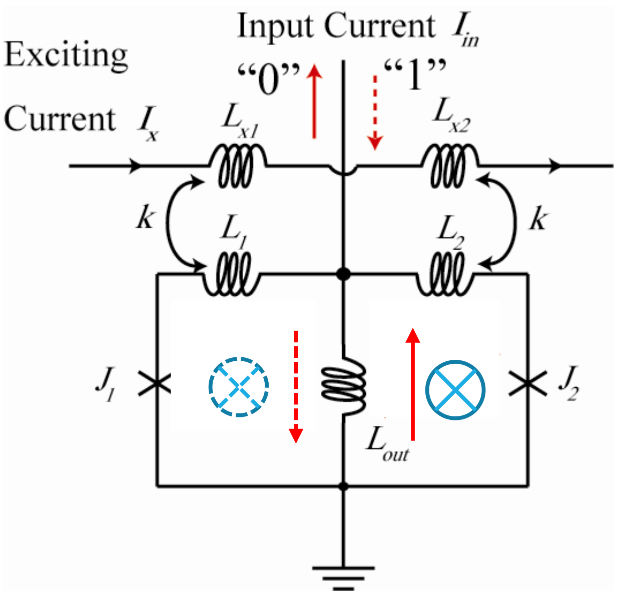
Disadvantage

- Transformers are needed for all the gates, indicating downsizing to sub-micron scale is difficult.
- High-frequency design technique is essential for operation.

AC-Powered Energy-Efficient SFQ Circuits

Circuits are driven by AC currents provided via transformers.

Example
Adiabatic Quantum Flux Parametron
(Yokohama Nat'l Univ.)



Advantage

- Very small energy consumption because of no phase jump in switching.
- All the logic operations are achieved based on a single 'majority' gate, leading to the robustness to the process variation.

Disadvantage

- Operating frequency is relatively low.
- Difficult to make long interconnects.
- DC offset currents are needed for operation.

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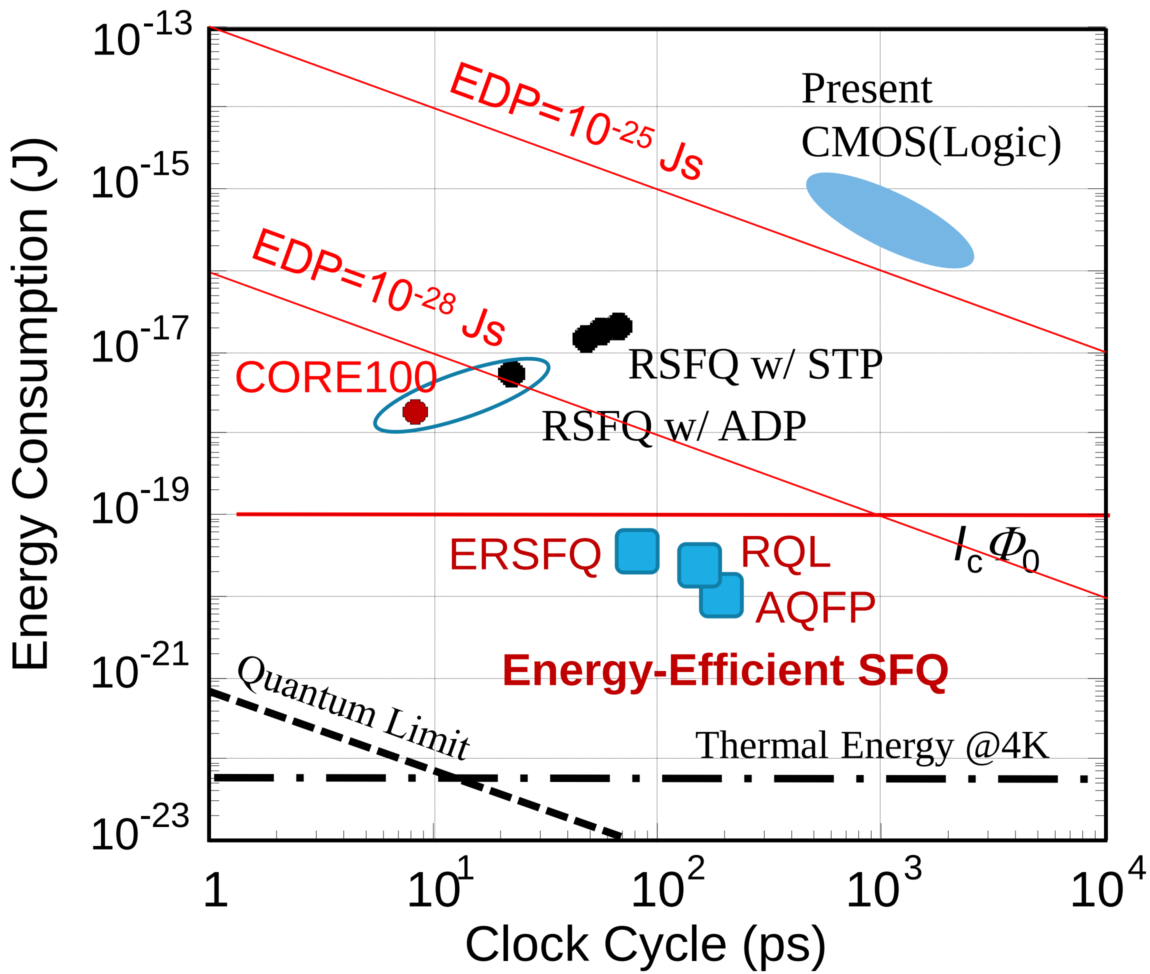
Energy-Efficiency in Integrated Circuits



$$\text{Energy Consumption} = \frac{\text{Total power x Clk cycle}}{\text{Number of devices}}$$

STP: AIST 2.5-kA/cm^2 Nb/AlO$_x$/Nb Standard Integrated Circuit Process.

ADP: AIST 10-kA/cm^2 Nb/AlO$_x$/Nb Advanced Integrated Circuit Process

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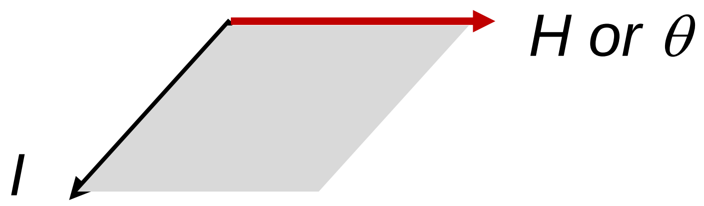
Superconducting Phase Engineering



Phase of a macroscopic wave-function of a superconductor or a superconducting ring is controlled with ferromagnetic materials.

Benefits of ferromagnetic materials

- Fixed flux biasing or Phase shift element (PSE)
  - **AC/DC converter**
  - Reduction of total bias currents
- Magnetization Reversal
  - Increased flexibility, *i.e.*, **reconfigurable circuits**
- Magnetic Josephson junction
  - Energy-efficient circuits based on π-phase-shift
  - Energy-efficient memories

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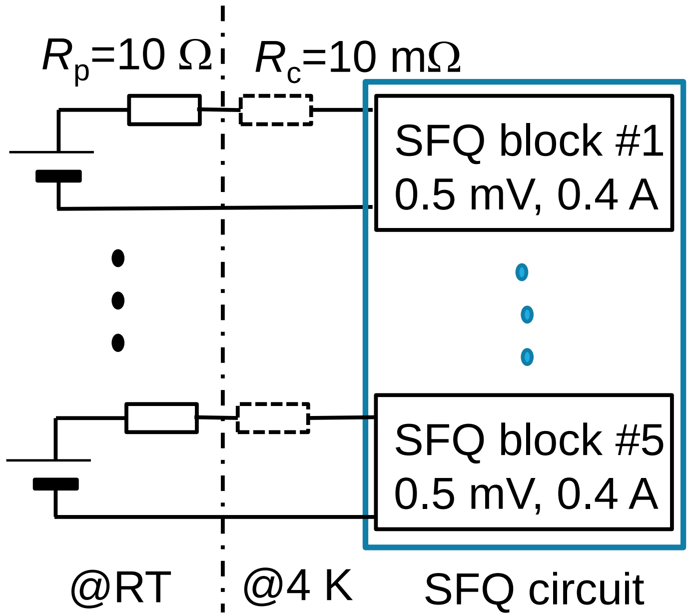
AC/DC Converter for DC-Powered SFQ Circuits

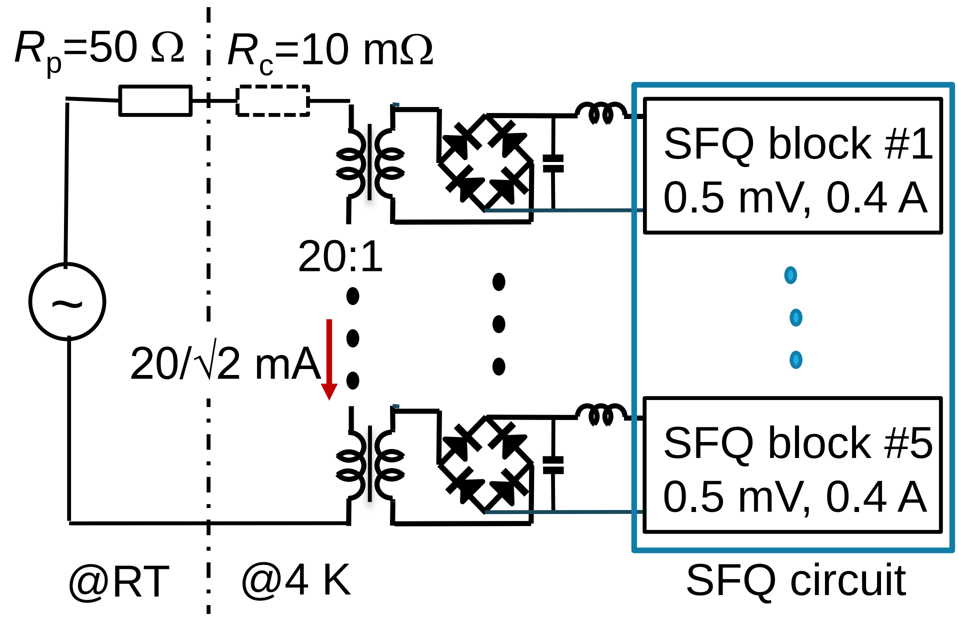


P_{supply}=8 W

P_{SFQ}=1 mW

$P_{contact}$=8 mW

Present



P_{supply}=10 mW $P_{contact}$≈0

P_{SFQ}=1 mW

After introduction of superconducting diodes

AC/DC converter is essential for DC-powered SFQ circuits.

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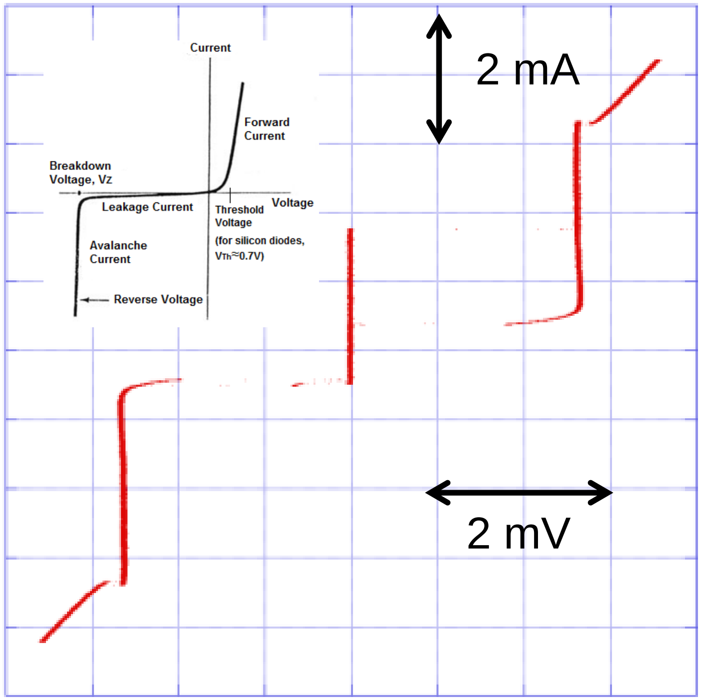
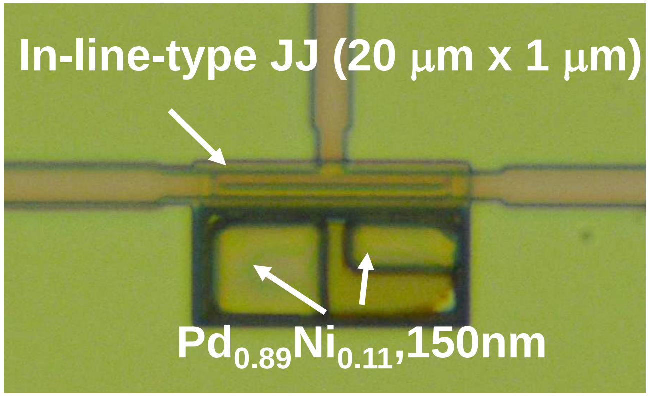
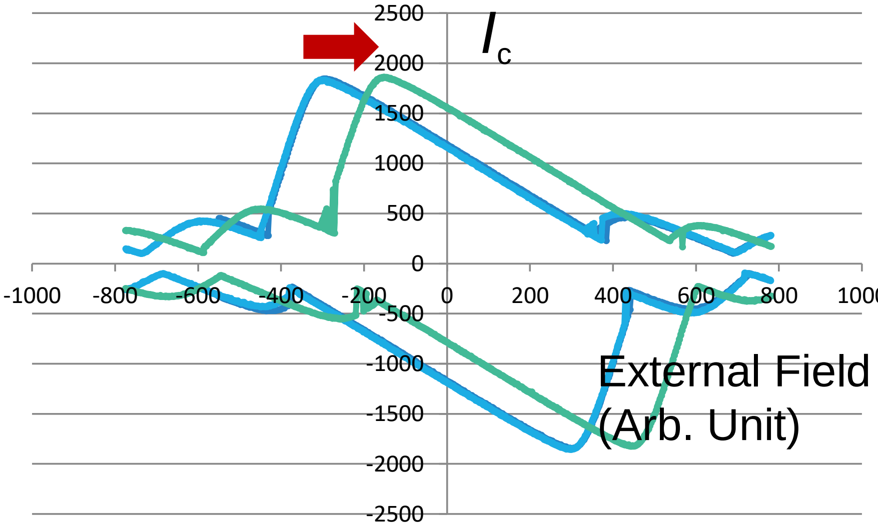
Superconducting Diode Based on Residual Magnetization







- A diode with V_{th}=0 is obtained.
- Critical currents can be controlled.

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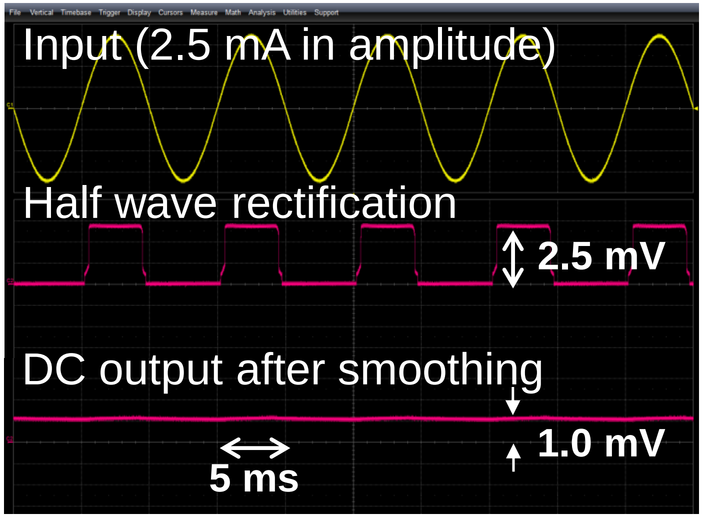
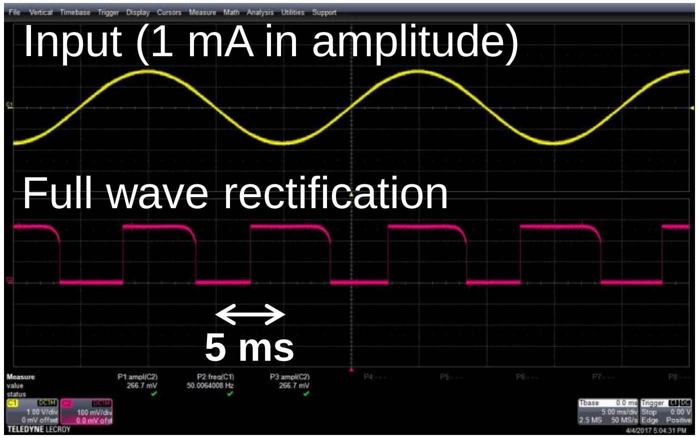
Rectification with Superconducting Diodes





We can control DC output voltages by changing the phase of the switching.
This might open superconducting power electronics.

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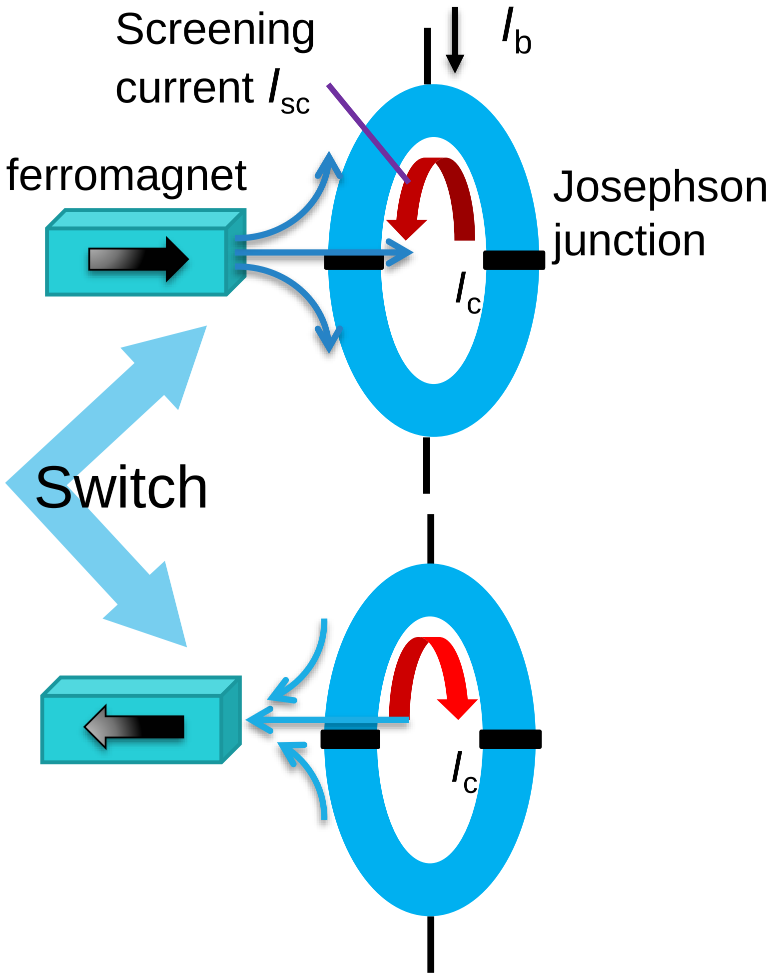
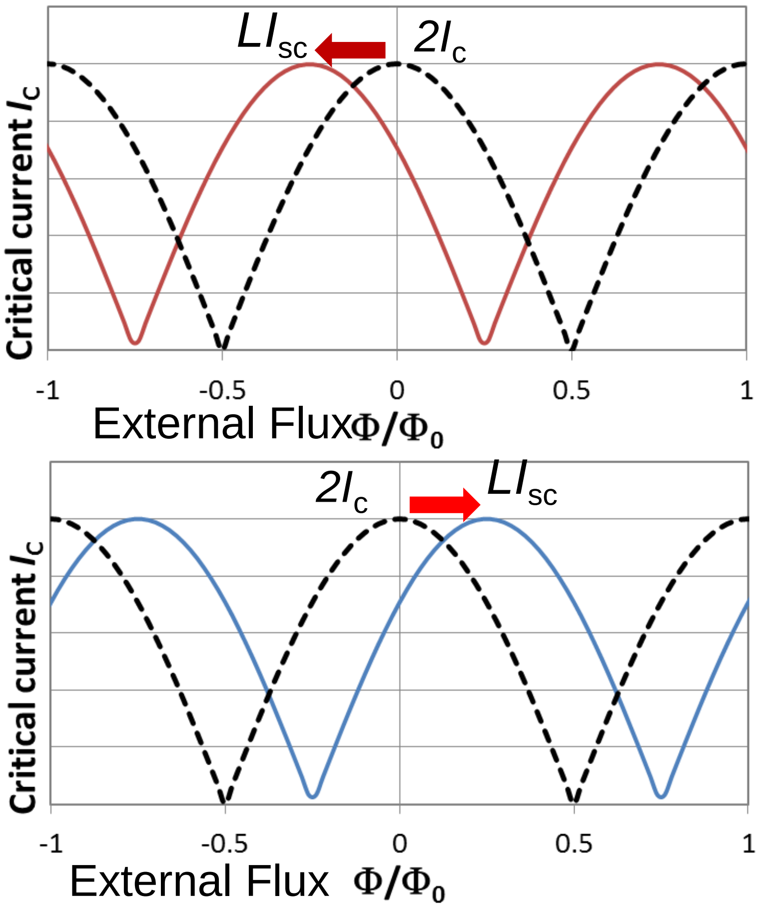
More Flexible Computing





SQUID modulation pattern

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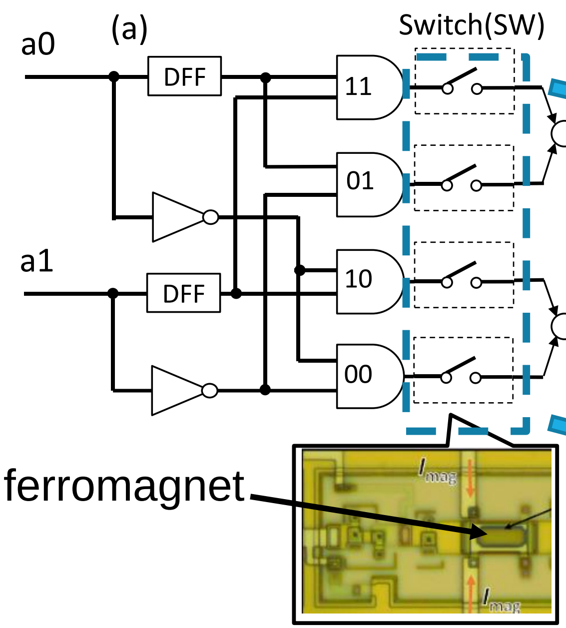
Demonstration of Look-Up Table



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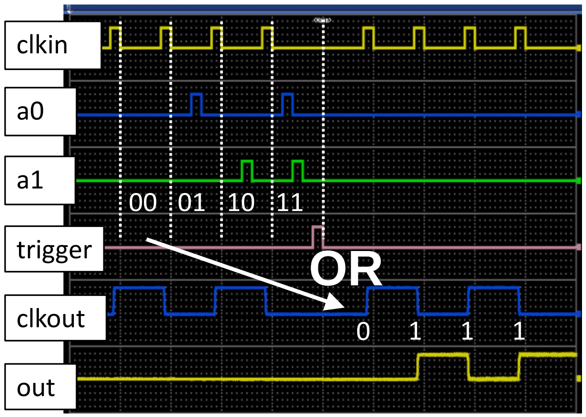

OFF
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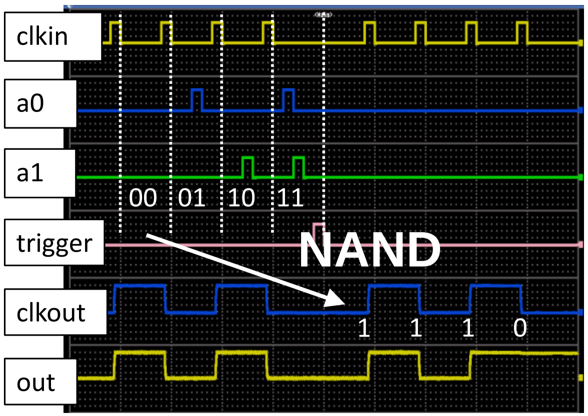

- Successfully demonstrate 2-input LUTs.
- Operate up to 52 GHz.

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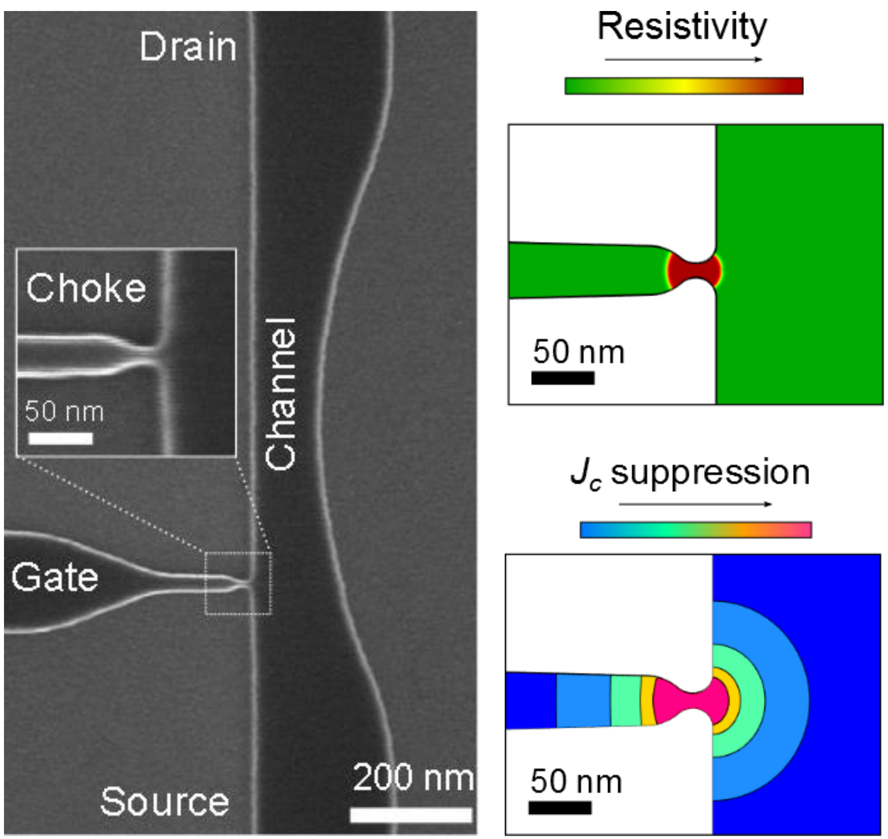
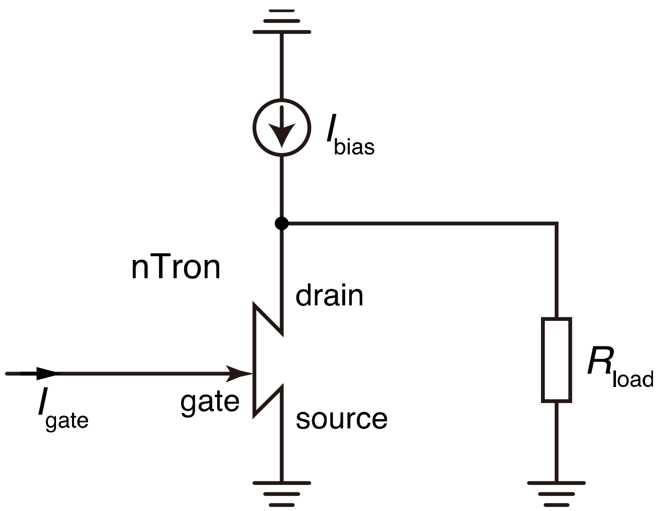
Nanowire Cryotron (nTron)





- ✓ Fabricated by a single NbN layer
- ✓ Switched by thermal assisting
- ✓ High output voltage (Sub-V)
- ✓ High-impedance (kΩ range)
- ✓ ~ 100 ps, 10^{-18} J/bit

A. N. McCaughan and K. K. Berggren, *Nano Lett.* **14** (2014)

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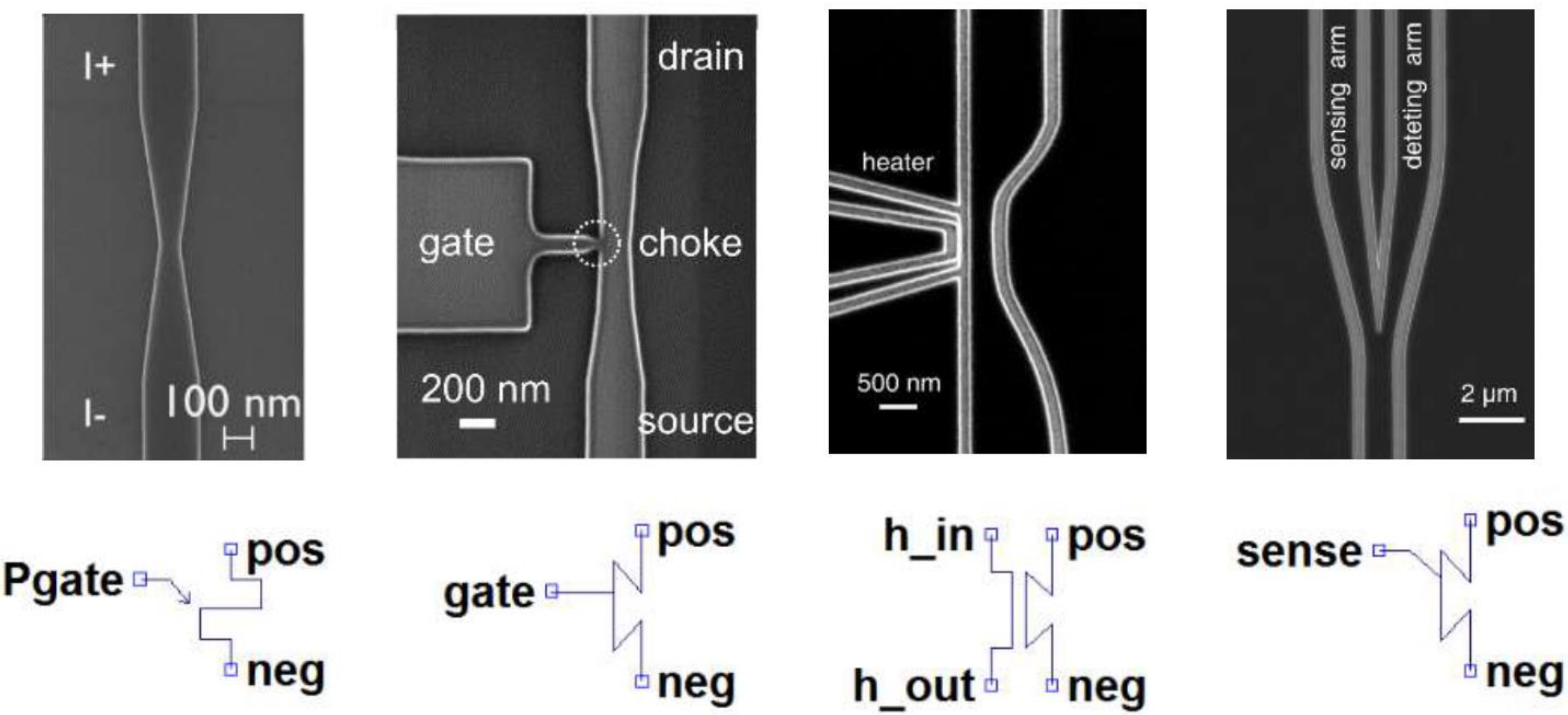
nTron Family (MIT)

Single nanowire SNSPD

NanoCryotron (nTron)

Gate isolated cryotron (hTron)

Current crowding cryotron (yTron)



Courtesy of Dr. Zhao (MIT)

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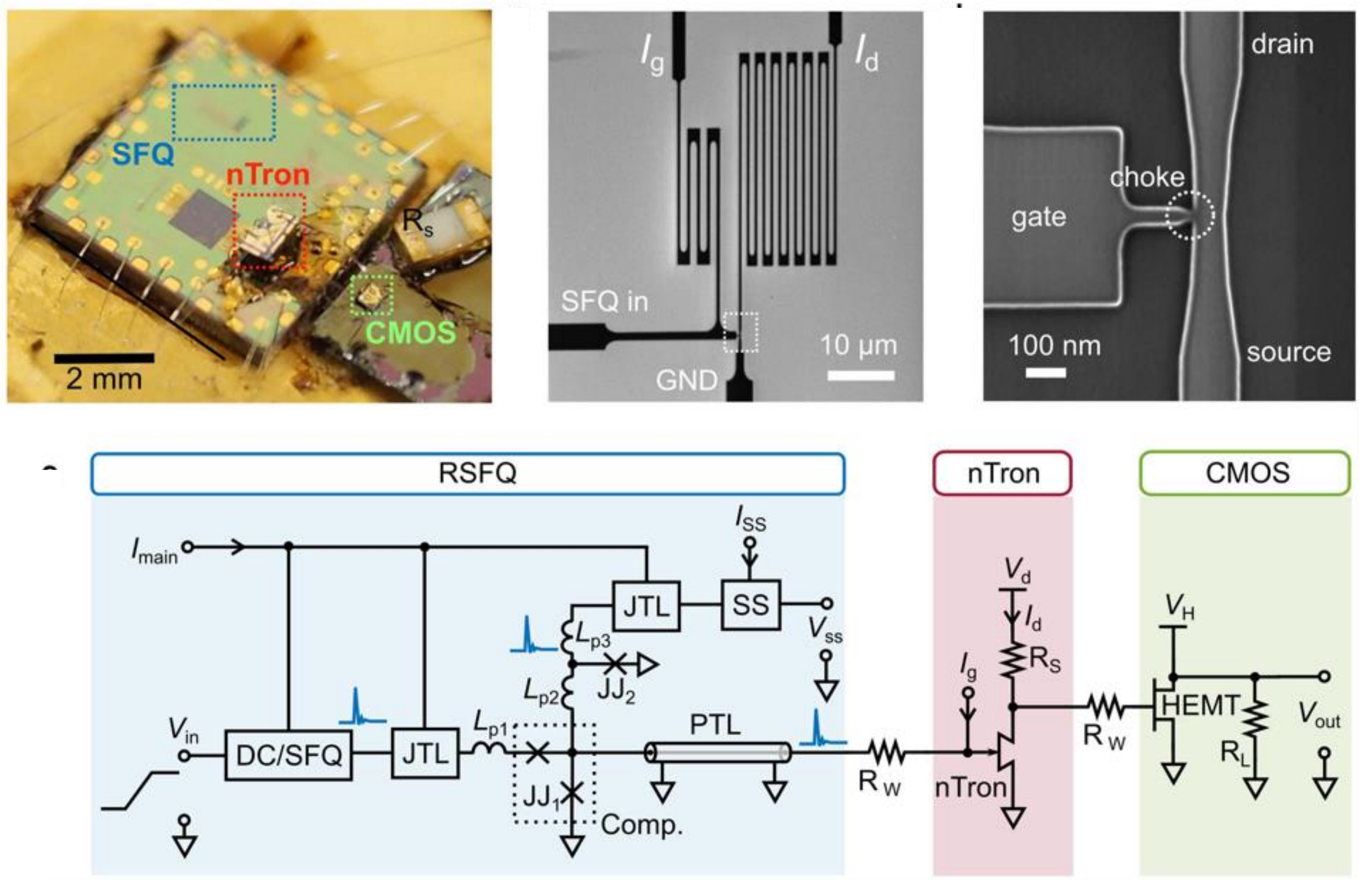
Demo. of nTron for Driving Semicon. Tr



nTron can serve as a voltage amplifier needed between SFQ circuits and semiconductor circuits.

Q.-Y. Zhao et al, *Supercond. Sci. Technol.* **30** (2017)

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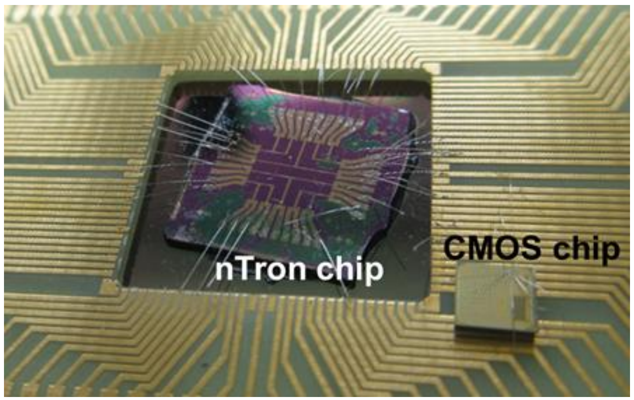
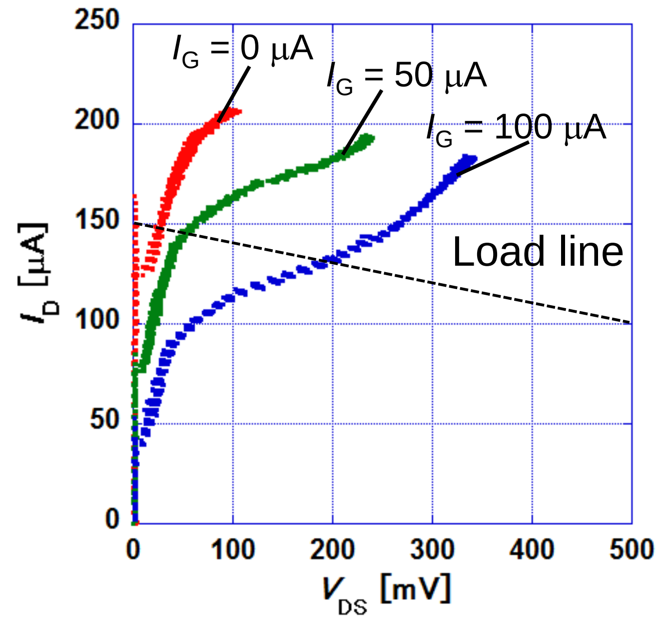
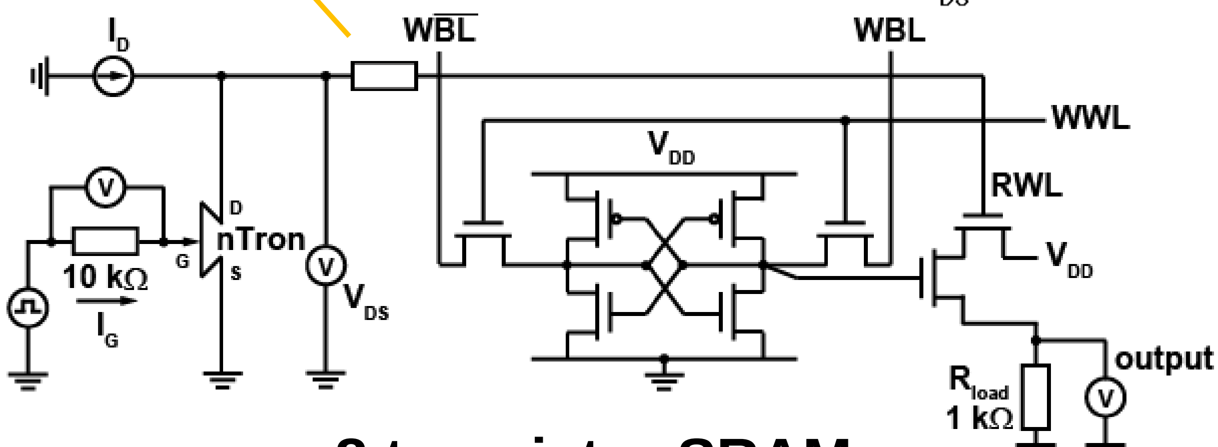
NbTiN nTron + CMOS memory cell





Al wire bonds



8 transistor SRAM

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
This keynote presentation Tu-KEY-01 was given at ISEC 2017.

Summary

- Classical RSFQ circuits have matured over the decades.
- Programs stored in embedded memories have been demonstrated and bit-parallel processing has been executed at 50 GHz.
- By introducing new concepts referred to as superconducting phase engineering and phonon engineering, the issues for the practical applications are resolved.
- Cryogenic digital circuit technology is really competitive in processing speed or energy-efficiency to semiconductor.
- Advancement in fabrication technology is needed.
- New technologies such as quantum information processing, deep learning should be introduced positively.

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Grazie tante